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# Radiation Exposure for Uranium Industry Workers

(work in progress - last updated 30 Oct 2006)

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## Workers: Standards

The applicable radiation dose standard for workers is 20 mSv/a (averaged over 5 years), and the fatal cancer risk is 0.04 per Sv, according to [ICRP60].

Exposure to 20 mSv/a over a work life of 40 years results in an excess lifetime fatal cancer risk of 3.2% (1 : 31).

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## Workers at Uranium Mine

### Source Term

The radon emanation rate from the Jabiluka ore deposit in Australia was determined at 15 Bq/m<sup>2</sup>·s per %U<sub>3</sub>O<sub>8</sub> (18 Bq/m<sup>2</sup>·s per %U) ore grade [Sonter2000]. For secular equilibrium of the uranium series nuclides, this corresponds to 0.142 Bq/m<sup>2</sup>·s per Bq<sub>Ra-226</sub>/g.

### Exposure of Miners

- **Inhalation of radon / radon progeny**

(typ. 69% of total dose for underground miners, and 34% for open pit miners [UNSCEAR1993] for 1985-1989)

See also: [Uranium Miner Health Risk Calculator](#) · [Radon Individual Dose Calculator](#)

- **External radiation**

For underground positions totally within ore, a gamma dose rate factor of 70 µSv/h per %U<sub>3</sub>O<sub>8</sub> (83 µSv/h per %U) ore grade was determined for the Jabiluka mine in Australia [Sonter2000]. External radiation represents typ. 28% of total dose for underground miners, and 60% for open pit miners. [UNSCEAR1993] for 1985-1989

- **Inhalation of uranium ore dust**

The effective dose from inhalation of 1 mg uranium ore of an ore grade of 0.1% U is 0.42 µSv (for higher ore grades, the dose increases correspondingly). The 20 mSv annual standard is equivalent to 47.6 g. This corresponds to a uranium ore concentration in air of 16.5 mg/m<sup>3</sup>. (See also: [Uranium Radiation Individual Dose Calculator](#))

(based on ICRP68 dose factors for insoluble compounds, breathing rate of 1.6 m<sup>3</sup>/h, working time of 1800 h/a, U-238 in equilibrium with progeny)

Inhalation of uranium ore dust represents typ. 3.2% of the total dose for underground miners, and 6.2% for open pit miners. [UNSCEAR1993] for 1985-1989

Typical individual doses vary within the range of 3 - 20 mSv/a (avg. 4.45 mSv/a) for underground miners, and within the range of 1 - 5 mSv/a (avg. 1.56 mSv/a) for open pit miners, with an average of 4.4 mSv/a over all uranium miners.

The collective dose for all 260,000 underground uranium miners worldwide is estimated at 1140 man-Sv/a, and for all 2500 open pit uranium miners at 3.76 man-Sv/a. This corresponds to 25.9 man-Sv per 1000 t uranium mined underground, and to 0.258 man-Sv per 1000 t uranium mined in open pits, with an average of 20 man-Sv per 1000 t for all uranium mined. [UNSCEAR1993] for 1985-1989

The expected number of fatal cancers in all uranium miners is 44 per year, or 0.8 per 1000 t uranium mined.

(see also [Health Impacts for Uranium Miners](#) · [Sample Calculations](#))

## Workers at Uranium mill

## Source Term

### Exposure of mill workers

- **Inhalation of radon / radon progeny**

(typ. 37% of total dose [UNSCEAR1993] for 1985-1989)

See also: [Radon Individual Dose Calculator](#)

- **inhalation of uranium ore dust**

The effective dose from inhalation of 1 mg [uranium ore](#) of an ore grade of 0.1% U is 0.42  $\mu$ Sv (for higher ore grades, the dose increases correspondingly). The 20 mSv annual standard is equivalent to 47.6 g. This corresponds to a uranium ore concentration in air of 16.5 mg/m<sup>3</sup>. (See also: [Uranium Radiation Individual Dose Calculator](#))

(based on ICRP68 dose factors for insoluble compounds, breathing rate of 1.6 m<sup>3</sup>/h, working time of 1800 h/a, U-238 in equilibrium with progeny)

- **inhalation of uranium concentrate dust**

The effective dose from inhalation of 1 mg [pure natural uranium](#) is 0.2 mSv. The 20 mSv annual standard is equivalent to 100 mg. This corresponds to a uranium concentration in air of 34.7  $\mu$ g/m<sup>3</sup>. (See also: [Uranium Radiation Individual Dose Calculator](#))

(based on ICRP68 dose factors for insoluble compounds, breathing rate of 1.6 m<sup>3</sup>/h, working time of 1800 h/a)

Inhalation of uranium dust represents typ. 47% of the total dose for uranium mill workers. [UNSCEAR1993] for 1985-1989

- **external radiation**

(typ. 16% of total dose [UNSCEAR1993] for 1985-1989)

Typical individual doses for uranium mill workers vary within the range of 0.1 - 13 mSv/a (avg. 6.3 mSv/a).

The collective dose for all 18,000 uranium mill workers worldwide is estimated at 116 man-Sv/a; this corresponds to 2.01 man-Sv per 1000 t uranium extracted. [UNSCEAR1993] for 1985-1989

The expected number of fatal cancers in all uranium mill workers is 4.64 per year, or 0.08 per 1000 t uranium extracted.

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## Workers at Heavy Water Reactor Fuel Plant

For use in heavy water reactors (HWR), the [uranium ore concentrate](#) is refined (purified) and converted to [UO<sub>2</sub>](#). Then it is formed into pellets and filled into fuel rods. The fuel rods are banded into fuel elements.

## Source Term

### Exposure of HWR fuel fabrication workers

- **external radiation**

- **inhalation of uranium dust**

The effective dose from inhalation of 1 mg pure natural uranium (as contained in [uranium ore concentrate](#) or [heavy water reactor fuel](#)) is 0.2 mSv. The 20 mSv annual standard is equivalent to 100 mg. This corresponds to a uranium concentration in air of  $34.7 \mu\text{g}/\text{m}^3$ . (See also: [Uranium Radiation Individual Dose Calculator](#))

(based on ICRP68 dose factors for insoluble compounds, breathing rate of  $1.6 \text{ m}^3/\text{h}$ , working time of 1800 h/a)

The average individual dose for a heavy water reactor fuel fabrication worker is 1.67 mSv/a. The collective dose for all 1140 HWR fuel fabrication workers worldwide is estimated at 1.9 man-Sv/a; this corresponds to 1.21 man-Sv per 1000 t fuel fabricated. [UNSCEAR1993] for 1985-1989  
The expected number of fatal cancers in all HWR fuel workers is 0.076 per year, or 0.048 per 1000 t fuel fabricated.

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## Workers at Magnox Reactor Fuel Plant

For use in Magnox reactors, the [uranium ore concentrate](#) is refined (purified) and converted to [uranium metal](#). This is formed into fuel rods. The fuel rods are clad and banded into fuel elements.

### Source Term

#### Exposure of Magnox fuel fabrication workers

- **external radiation**

- **inhalation of uranium dust**

The effective dose from inhalation of 1 mg pure natural uranium (as contained in [uranium ore concentrate](#) or [Magnox reactor fuel](#)) is 0.2 mSv. The 20 mSv annual standard is equivalent to 100 mg. This corresponds to a uranium concentration in air of  $34.7 \mu\text{g}/\text{m}^3$ . (See also: [Uranium Radiation Individual Dose Calculator](#))

(based on ICRP68 dose factors for insoluble compounds, breathing rate of  $1.6 \text{ m}^3/\text{h}$ , working time of 1800 h/a)

- **pyrophoricity hazard from uranium metal**

Finely divided particles of uranium metal can ignite and require special precautions.

The average individual dose for a Magnox fuel fabrication worker is 3.12 mSv/a. The collective dose for all 1,110 Magnox fuel fabrication workers in the United Kingdom is estimated at 3.48 man-Sv/a; this corresponds to 4.29 man-Sv per 1000 t fuel fabricated. [UNSCEAR1993] for 1985-1989  
The expected number of fatal cancers in all UK Magnox fuel workers is 0.14 per year, or 0.17 per 1000 t fuel fabricated.

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## Workers at Uranium Conversion and Enrichment Plant

For use in light water reactors, the [uranium ore concentrate](#) is refined (purified) and converted to [uranium hexafluoride \( \$\text{UF}\_6\$ \)](#) in a conversion plant.

At the enrichment plant, the concentration of the fissile uranium isotope U-235 in the uranium hexafluoride is raised from its natural grade of 0.71% to the range of 3 - 5%.

## Source Term

Additional hazards exist, if not only uranium of natural origin is processed, but also uranium recovered from reprocessing of spent nuclear fuel. The latter uranium is contaminated with radioactive transuranics and fission products.

The Paducah (Kentucky) uranium enrichment plant, for example, processed recycled uranium between 1953 and 1976. Paducah received approximately 90,000 metric tonnes of recycled uranium containing an estimated 3.6 ppb of plutonium-239, 0.2 ppm of neptunium-237 and 7.3 ppm of technetium-99. The majority of the plutonium and neptunium was separated out as waste during the initial chemical conversion to uranium hexafluoride. Because of this, only a fraction (0.03%) of the plutonium contamination was actually introduced to the gaseous diffusion cascade. ([DOE Press Release Sep 29, 1999](#) )

Moreover, uranium recycled from spent fuel contains several artificial uranium isotopes, such as U-232, U-233, U-236, and U-237. Uranium-232 is of special concern, since some of its decay products are strong gamma emitters (in particular thallium-208).

## Exposure of conversion and enrichment workers

- inhalation of uranium concentrate dust**

The effective dose from inhalation of 1 mg [pure natural uranium](#) is 0.2 mSv. The 20 mSv annual standard is equivalent to 100 mg. This corresponds to a uranium concentration in air of 34.7  $\mu\text{g}/\text{m}^3$ . (See also: [Uranium Radiation Individual Dose Calculator](#))

If the uranium was recycled from spent fuel, the inhalation dose from 1 mg is 0.66 mSv. The 20 mSv annual standard is equivalent to 30.3 mg. This corresponds to a uranium concentration in air of 10.5  $\mu\text{g}/\text{m}^3$ .

(based on ICRP68 dose factors for insoluble compounds, breathing rate of 1.6  $\text{m}^3/\text{h}$ , working time of 1800 h/a, initial enrichment to 3.5%, burnup of 39 GWd/tHM, storage time of 5 years after unload)

- external radiation from  $\text{UF}_6$**

The gamma dose rates measured at the surface of a [uranium hexafluoride](#) storage cylinder filled with [depleted uranium hexafluoride](#) are typically about 2 - 3 mrem/h (20 - 30  $\mu\text{Sv}/\text{h}$ ), decreasing to about 1 mrem/h (10  $\mu\text{Sv}/\text{h}$ ) at a distance of 30 cm [DOE1999] p.1-2.

For cylinders containing uranium recycled from spent fuel, gamma dose rates are 10 - 100 times higher than for uranium from natural sources:

### Gamma dose rate at $\text{UF}_6$ cylinder of type 30B

(for initial enrichment to 3.2% and burnup of 33 GWd/tHM)

	U-235 conc. [wt_%]	Storage time [years]	Dose rate [ $\mu\text{Sv}/\text{h}$ ]		
			surface	1 m	2 m
enriched natural U	3.2%	-	4	1	0.4
recycled U	0.93%	0.25	40	10	4
		2	90	22	9

enriched recycled U	3.44%	0.25	90	22	9
		2	400	100	40

The type 30B cylinder has a nominal diameter of 30 inches (76.2 cm) and contains max. 2277 kg of UF<sub>6</sub>

Source: [Neghabian1991] p.168 - 186

For higher burnups, dose rates rise considerably, in particular after longer storage times:

### Gamma dose rate at UF<sub>6</sub> cylinder of type 30B

(for initial enrichment to 4.4% and burnup of 50 GWd/tHM)

	U-235 conc. [wt_%]	Storage time [years]	Dose rate [μSv/h]		
			surface	1 m	2 m
enriched natural U	4.4%	-	5	1.5	0.6
recycled U	0.86%	0.25	50	13	5
		2	160	40	16
enriched recycled U	4.93%	0.25	220	55	22
		2	1200	300	120

The type 30B cylinder has a nominal diameter of 30 inches (76.2 cm) and contains max. 2277 kg of UF<sub>6</sub>

Source: [Neghabian1991] p.168 - 186

In addition to gamma radiation, UF<sub>6</sub> cylinders also emit neutron radiation. The neutron radiation results from an (Alpha,n)-reaction of the uranium's alpha radiation with fluorine (see: [Alpha-Neutron Reaction Calculator](#)). Near cylinders carrying enriched uranium, up to 70% of the radiation exposure can be due to the neutron radiation. Near cylinders carrying depleted uranium, up to 20% of the radiation exposure can be due to the neutron radiation. [Urenco2002]

- external radiation from "empty" cylinders containing heels**

After unloading of UF<sub>6</sub> by heating in an autoclave, the residue remaining in a cylinder (called "[heels](#)") emits gamma radiation (mainly from Pa-234m). As, in an "empty" cylinder, the gamma radiation is no longer shielded by the uranium, it can reach the cylinder surface nearly unhindered. While the gamma radiation dose rate at 30 cm from a full cylinder carrying natural UF<sub>6</sub> reaches a few μSv/h, the dose rate rises approx. one-hundred-fold to 500 μSv/h at 30 cm from the bottom of the cylinder after unloading, making the "empty" cylinders the source of the highest gamma radiation fields in an enrichment plant [Bailey1975].

For cylinders carrying recycled UF<sub>6</sub>, the strong gamma emitter thallium-208 remains with the heels in the cylinder, causing even higher gamma dose rates: such cylinders may not be suitable for transport and must be cleaned first. [IAEA1994]

- inhalation of toxics during accidents**

If the whole contents of a UF<sub>6</sub> cylinder is released during a fire, lethal air concentrations of toxic substances can occur within distances of 500 to 1,000 meters.

- irradiation from criticality accidents**

Persons standing nearby a criticality excursion may be exposed to lethal radiation doses of tens of

Sieverts (see for example: [Criticality accident at Tokai nuclear fuel plant](#)).

The average individual dose for an uranium enrichment worker is 0.08 mSv/a. The collective dose for the 5,000 enrichment workers for whom data is reported is estimated at 0.43 man-Sv/a. [UNSCEAR1993] for 1985-1989

The average individual dose for cylinder yard workers at three U.S. enrichment plants ranged between 0.16 - 1.96 mSv/a during the years 1990-1995 [DOE1999] p.3-15/32/51.

## Workers at Light Water Reactor Fuel Fabrication Facilities

In the fabrication plant for light water reactor fuel, the [enriched uranium hexafluoride](#) is converted to [UO<sub>2</sub>](#). Then it is formed into pellets and filled into fuel rods. The fuel rods are banded into fuel elements.

### Source Term

#### Exposure of LWR fuel fabrication workers

- **external radiation**

- **inhalation of uranium dust**

The effective dose from inhalation of 1 mg [uranium enriched](#) to 3.5% is 0.676 mSv. The 20 mSv annual standard is equivalent to 29.6 mg. This corresponds to a uranium concentration in air of 10.3 µg/m<sup>3</sup>. (See also: [Uranium Radiation Individual Dose Calculator](#))

If the uranium was recycled from spent fuel, the inhalation dose from 1 mg is 2.86 mSv. The 20 mSv annual standard is equivalent to 7.0 mg. This corresponds to a uranium concentration in air of 2.4 µg/m<sup>3</sup>.

(based on ICRP68 dose factors for insoluble compounds, breathing rate of 1.6 m<sup>3</sup>/h, working time of 1800 h/a, burnup of 39 GWd/tHM, storage time of 5 years after unload)

- **criticality accidents**

Persons standing nearby a criticality excursion may be exposed to lethal radiation doses of tens of Sieverts.

The average individual dose for a light water reactor (LWR) fuel fabrication worker is 0.45 mSv/a. The collective dose for all 24,000 LWR fuel fabrication workers worldwide is estimated at 11 man-Sv/a; this corresponds to 1.6 man-Sv per 1000 t fuel fabricated. [UNSCEAR1993] for 1985-1989

The expected number of fatal cancers in all LWR fuel workers is 0.44 per year, or 0.064 per 1000 t fuel fabricated.

## Workers: Summary

### Workers' Dose Summary

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	no. of workers	avg. individual dose [mSv/a]	collective dose [man-Sv/a]
all uranium miners	260,000	4.4	1,100
uranium mill workers	18,000	6.3	116
HWR fuel facility workers	1,140	1.67	1.9
Magnox fuel facility workers	1,110	3.12	3.48
enrichment workers	5,000	0.08	0.43
LWR fuel facility workers	24,000	0.45	11
AGR fuel facility workers	1,850	2.97	5.51
TOTAL	311,100	3.98	1,238

[UNSCEAR1993] for 1985-1989 (*minor inconsistencies in ref.*)

### Workers' Risk Summary

	no. of workers	excess lifetime cancer risk*		collective risk [fatalities per year]
all uranium miners	260,000	0.7%	1 : 142	44
uranium mill workers	18,000	1.01%	1 : 99	4.64
HWR fuel facility workers	1,140	0.27%	1 : 374	0.076
Magnox fuel facility workers	1,110	0.5%	1 : 200	0.14
enrichment workers	5,000	0.013%	1 : 7812	0.017
LWR fuel facility workers	24,000	0.072%	1 : 1389	0.44
AGR fuel facility workers	1,850	0.48%	1 : 210	0.22
TOTAL	311,100	0.64%	1 : 156	49.5

\* based on 40 working years

based on [UNSCEAR1993] for 1985-1989, using risk factor of 0.04 per Sv


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see also:

U.S. DOE: [DOE Standard - Guide of Good Practices for Occupational Radiological Protection in Uranium Facilities, August 2000 / October 2000](#)  (1.2M PDF)

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